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APOLLO EXPERIENCE REPORT — PRESSURE VESSELS

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16. Abstract

The Apollo spacecraft pressure vessels, associated problems and resolutions, and related experience in evaluating potential problem areas are discussed. Information is provided that can be used as a guideline in the establishment of baseline criteria for the design and use of lightweight pressure vessels. One of the first practical applications of the use of fracture-mechanics technology to protect against service failures was made on Apollo pressure vessels. Recommendations are made, based on Apollo experience, that are designed to reduce the incidence of failure in pressure-vessel operation and service.

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APOLLO EXPERIENCE REPORT

PRESSURE VESSELS

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SUMMARY

Apollo spacecraft pressure vessels were designed using safety factors as low as 1.5 to save weight. The relatively low safety factors, combined with the criticality of a vessel failure, required that stringent fabrication requirements and controls be maintained throughout the vessel programs to ensure production of quality vessels. Additionally, postfabrication analytical techniques were introduced to confirm and control safe vessel operation.

No problems were experienced that were a direct result of reduced safety-factor levels. Major vessel problems involved isolated instances of materials incompatibility with pressurants, of inadequate process control, and of materials anomalies. However, it has been shown that reduced safety factors may increase the susceptibility of materials to stress corrosion or incompatibility problems.

The resolution of each problem provided a resultant increase in the knowledge necessary to ensure safe operation as reflected in several recommendations concerning design, fabrication, use, and management of lightweight pressure vessels. Specific identification and assignment of responsibility for spacecraft pressure vessels was necessary to accomplish effective control of vessel fabrication and use.

INTRODUCTION

The Apollo spacecraft pressure vessels comprise a significant part of the dry structural weight of the spacecraft. Seventy-one vessels are used in the command module (CM), service module (SM), and lunar module (LM); the launch escape system (LES) uses three rocket motor cases that become pressurized when fired. Each of the vessels constitutes a potential single failure point for critical subsystems and contains stored energy at operating pressures that could be catastrophic to the spacecraft should rupture occur.

Historically, high safety factors (ratio of design burst pressure to maximum design operating pressure) have been used in the design of commercial pressure vessels to compensate for unknowns in pressure-vessel fabrication and service. A safety

factor of 4.0 was considered a minimum. In the early 1960's, the U.S. Air Force developed a new technology for fabrication methods and materials control by means of stringent specification requirements that minimized risk and justified a safety factor of 2.0 for pressure vessels used in high-performance aircraft.

Safety factors of 2.0 on some pressure vessels used in the Apollo spacecraft systems became impracticable because of the associated weight penalty. As a result, several Apollo pressure vessels were designed to a minimum safety factor of 1.5. This unprecedented minimum safety factor for vessels in manned systems combined with the criticality of a vessel failure required that every known precaution be taken in fabrication and use to ensure safe vessel operation. Despite the precautions, a few failures and related problems were experienced. The resolution of these problems and the steps taken to preclude recurrence, including the introduction of additional precautions and the application of fracture-mechanics technology in postfabrication analysis, are discussed in this report.

DESIGN AND TEST

Design data and other pertinent information for Apollo spacecraft pressure vessels are presented in tables I and II. Many of the larger or more numerous vessels have safety factors as low as 1.5 to achieve a lightweight structure. The locations and uses of many of the vessels throughout the spacecraft are shown in figures 1 to 9. The assimilation of pressure vessels in the spacecraft design and the relationship to spacecraft operation are illustrated in those figures.

The Apollo spacecraft was designed and built in Block I and Block II configurations for the command and service modules. Essentially, Block I vehicles did not contain all the systems necessary for docking and lunar flight and were used unmanned to qualify various Apollo subsystems. Block II vehicles were fully configured for manned lunar missions. For the Block II configurations, some minor changes were made in the pressure-vessel designs for the service propulsion system (SPS), and vessel additions were made to the SM reaction control systems (RCS). Generally, the SPS helium and propellant vessels maintained the same overall dimensions and operating stresses, but operating pressures and wall thickness were reduced. Materials and processes remained the same. Two vessels were added to each SM RCS panel to provide additional RCS capacity for the Block II configuration. These additional vessels were of the same design as the CM RCS vessels.

Rigorous qualification tests (vibration, shock, acceleration, pressure cycling, and burst) were performed on production vessels of each type to demonstrate attainment of design requirements. The tests performed on each vessel are identified in table III. In some cases, the qualification of Block I vessels sufficed for Block II configuration. Each qualification vessel was given a nondestructive test (NDT) evaluation and was acceptance tested (proof pressurization and leak test) before the qualification test, as all production vessels have been tested before delivery. Subsequently, the number of pressurizations, the fluids, the pressure levels, and the temperatures have been controlled to ensure safe test conditions and adequate flight capability. This control has been accomplished by means of the regulation of spacecraft-systems tests involving vessel pressurizations through the application of fracture-mechanics criteria.

TABLE I. - APOLLO COMMAND AND SERVICE MODULE PRESSURE VESSELS

Pressure vessel		Quantity required	Vessel dimensions, in.			Vessel material	Design pressure, psi			Normal operating pressure, psi	Design safety factor	Actual burst pressure, psi
Use	Location		Diameter	Length	Thickness		Limit	Proof	Burst			
Pressure, helium	CM RCS	2	9.20	--	0.102	Titanium 6Al-4V	5000	6667	7500	4150	1.5	7950 and 8900
Propellant, oxidizer	CM RCS	2	12.6	19.907	.022	Titanium 6Al-4V	360	525	540	291	1.5	885 and 1043
Propellant, fuel	CM RCS	2	12.6	17.32	.022	Titanium 6Al-4V	360	525	540	291	1.5	885 and 1043
Pressure,[a] helium	SM SPS	2	40.17	--	.366	Titanium 6Al-4V	3685	4910	5540	3600	1.5	8100
Propellant,[a] oxidizer storage	SM SPS	1	45	153.05	.047 to .025	Titanium 6Al-4V	225	300	337.5	186	1.5	413
Propellant,[a] fuel storage	SM SPS	1	45	153.05	.047	Titanium 6Al-4V	225	300	337.5	186	1.5	413
Propellant,[a] oxidizer sump	SM SPS	1	51	152.30	.054 to .028	Titanium 6Al-4V	225	300	337.5	186	1.5	413
Propellant,[a] fuel sump	SM SPS	1	51	152.38	.054 to .028	Titanium 6Al-4V	225	300	337.5	186	1.5	413
Pressure, gaseous nitrogen	SM SPS	2	4.92	9.16	.135	Stainless steel AM 350	2900	5000	7500	2550	2.5	9820 and 10 000
Pressure, helium	SM RCS	4	12.0	--	.135	Titanium 6Al-4V	4500	5985	7000	4150	1.55	8000
Scientific instrument module panoramic camera, nitrogen (J mission)	--	1	12.0	--	.135	Titanium 6Al-4V	4500	5985	7000	4400	1.55	8000
Oxygen surge	CM ECS[b]	1	13.0	--	.033 to .078	Inconel 718	1020	1356	1530	900	1.5	2340 and 2880
Gaseous oxygen (rapid repressurization)	CM ECS	3	7.0	--	--	Inconel 718	1210	1600	1800	900	1.5	2767 and 3078
Waste water	--	1	12.25	17.1	.050	Al-6061-T6	40	60	72	32	1.8	120
Potable water	--	1	12.25	12.1	.050	Al-6061-T6	40	60	72	32	1.8	120
Glycol	--	1		Rectangular		Al-6061-T6	60	90	150	40	2.5	>150
LES	--	1	26.2	168	.209	4335V steel	1725	2450	3370	1600	1.95	3726
Pitch control	--	1	8.8	22	.102	4335V steel	2247	3000	3740	1460	1.65	3970 and 4088
Tower jettison	--	1	25	24.8	.106	4335V steel	1700	1955	2550	1330	1.50	2925 and 2950
Propellant, primary oxidizer	SM RCS	4	12.6	27.6	.022	Titanium 6Al-4V	248	360	372	185	1.5	567
Propellant, primary fuel	SM RCS	4	12.6	22.7	.022	Titanium 6Al-4V	248	360	372	185	1.5	603
Propellant, secondary oxidizer	SM RCS	4	12.6	19.907	.022	Titanium 6Al-4V	248	480	540	185	1.5	885 and 1043
Propellant, secondary fuel	SM RCS	4	12.6	17.32	.022	Titanium 6Al-4V	248	480	540	185	1.5	885 and 1043
Cryogenic, liquid oxygen	SM EPS[c]	[d]2	25.5 interior diameter	--	.060 wall	Inconel 718	1020	1356	1530	900	1.5	1873 ambient
Cryogenic, liquid hydrogen	SM EPS	[d]2	28.24	--	.045	Titanium 5Al-2.5Sn	285	400	450	225 and 260	1.5	775 and 812 ambient
Pressure, fuel cell gaseous nitrogen	SM EPS	3	6.0	--	.099	Titanium 5Al-2.5Sn	1500	3000	5180	1500	2.0	9400 and 10 000

[a]Data for Block II vessels only.

[b]Environmental control system.

[c]Electrical power system.

[d]Increased to three, effective Apollo 14.

TABLE II. - APOLLO LUNAR MODULE PRESSURE VESSELS

Pressure vessel		Quantity required	Vessel dimensions, in.			Vessel material	Design pressure, psi			Normal operating pressure, psi	Design safety factor	Actual burst pressure, psi
Use	Location		Diameter	Length	Thickness		Limit	Proof	Burst			
Water, ascent stage	ECS	2	14.2	--	0.027	Aluminum 6061	50	64	96	47	1.9	314
Water, descent stage	ECS	1	28.06	32.5	.040	Aluminum 6061	50	64	96	47	1.9	>134.8 and 246
Gaseous oxygen storage, ascent stage	ECS	2	11.97	14.500	.029	Inconel 718	1000	1330	1500	850	1.5	2070 and 246
Gaseous oxygen storage, descent stage	ECS	1	21.72	23.522	.123	D6AC	3000	3990	4500	2690	1.5	5400 and 5360
Pressure, helium storage	ECS	2	12.000	--	.099	Titanium 6Al-4V	3500	4650	5250	3050	1.5	5800 and 5700
Propellant, fuel	RCS	2	12.5	32.206	.020 to .017	Titanium 6Al-4V	250	333	375	179	1.5	589 and 622
Propellant, oxidizer	RCS	2	12.5	38.819	.025 to .017	Titanium 6Al-4V	250	333	375	179	1.5	767 and 775
Pressure, helium storage	APS[a]	2	22.25	--	.198	Titanium 6Al-4V	3500	4650	5250	3050	1.5	5740 and 5500
Propellant, fuel	APS	1	49.4	--	.032	Titanium 6Al-4V	250	333	388	184	1.5	452
Propellant, oxidizer	APS	1	49.4	--	.032	Titanium 6Al-4V	250	333	388	184	1.5	452
Supercritical helium	--	1	26.9	--	.129	Titanium 5Al-2.5Sn	1710	2274	3420	1555	2.0	3728
Pressure, helium storage	DPS[b]	1	14.9	--	.064	Titanium 6Al-4V	1750	2328	2625	1640	1.5	3100
Propellant, fuel	DPS	2	51.00	70.28	.065 to .033	Titanium 6Al-4V	270	360 [c]430	405	246	1.5	467 475 415
Propellent, oxidizer	DPS	2	51.00	70.28	.065 to .033	Titanium 6Al-4V	270	360 [c]430	405	246	1.5	467 475 415

[a]Ascent propulsion system.
[b]Descent propulsion system.
[c]Pressure for liquid-nitrogen proof test.

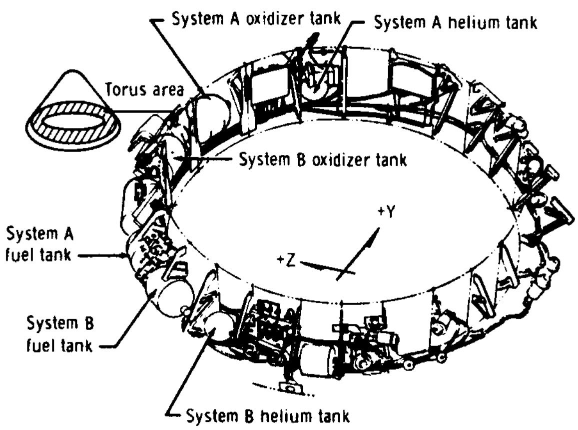


Figure 1. - Command module reaction control system vessels.

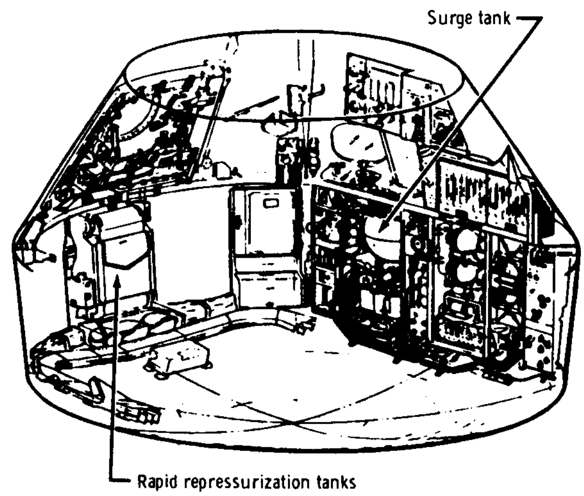


Figure 2. - Command module environmental control system oxygen supply vessels.

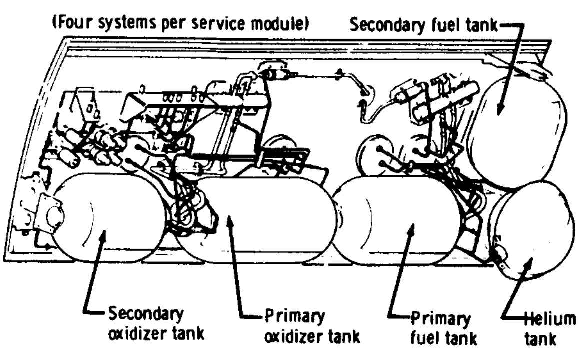


Figure 3. - Typical service module reaction control system quad vessels — Block II.

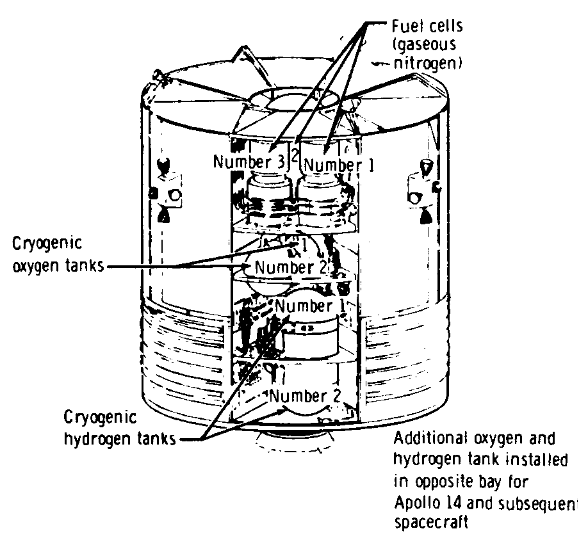


Figure 4. - Service module electrical power system vessels.

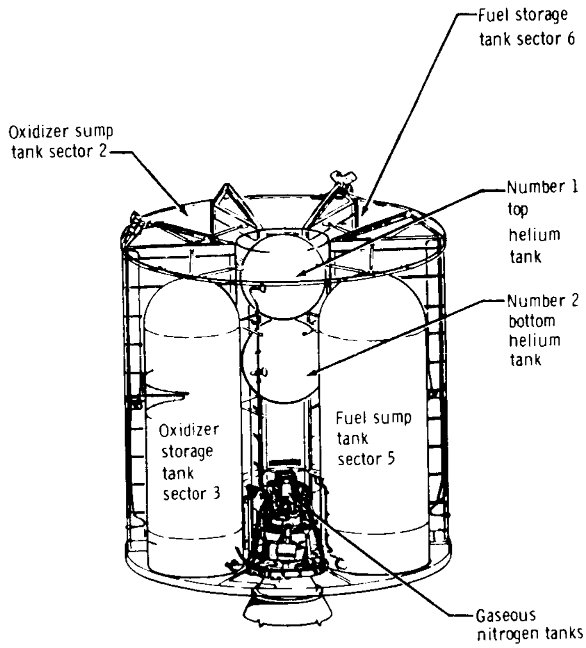


Figure 5. - Service module service propulsion system vessels — Block II.

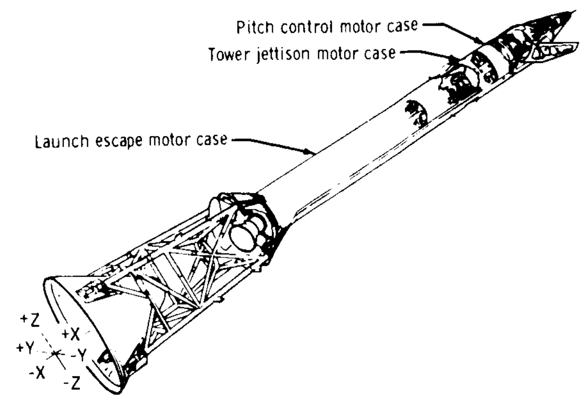


Figure 6. - Launch escape system vessels.

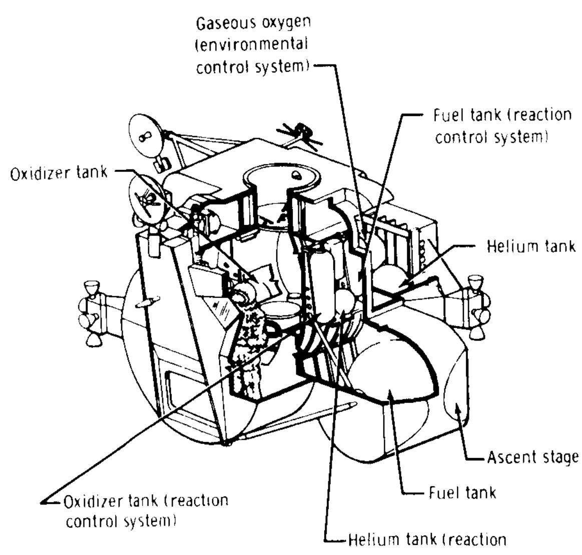


Figure 7. - Lunar module ascent stage vessels.

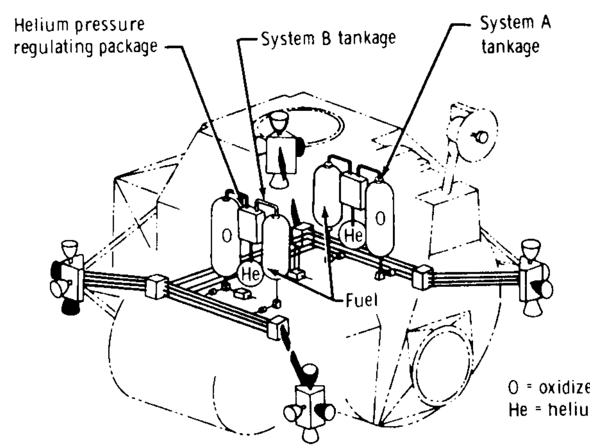


Figure 8. - Lunar module reaction control system vessels.

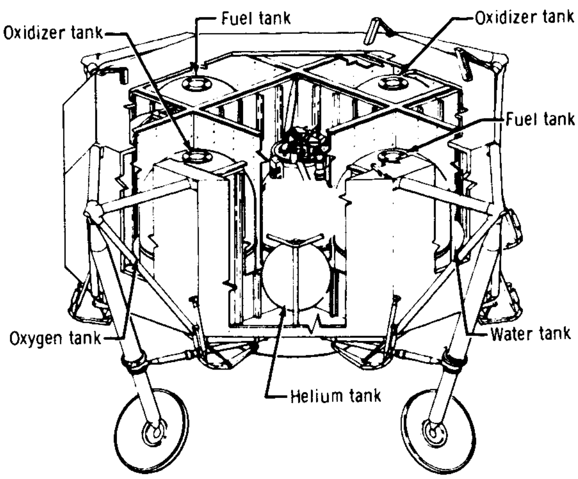


Figure 9. - Lunar module descent stage vessels.

Significant performance data on Apollo vessels have been generated during live propulsion-system tests at the NASA White Sands Test Facility (WSTF). Generally, a spacecraft vessel receives 10 to 12 pressure cycles during its lifetime; however, many of the flight-type vessels at the WSTF have completed, without incident, more than 350 cycles to or above operating pressure. This high degree of success is attributed largely to the close control of vessel fabrication and use that has been exercised on the Apollo Program and on the use of fracture-mechanics technology to predict safe vessel operation.

TABLE III. - SPACECRAFT PRESSURE-VESSEL QUALIFICATION

Tank function	Test performed				
	Vibration	Shock	Creep	Cyclic	Burst
Service propulsion system					
Pressurization Block I	X	--	--	X	X
	X	X	X	X	X
Oxidizer Block I	--	--	--	--	X
	--	X	X	--	X
	X	--	--	X	X
	X	X	X	X	X
	--	--	X	--	X
Fuel Block I	X	--	--	--	X
	--	X	X	--	X
	X	--	--	X	X
	X	X	X	X	X
Sump Block II	X	--	X	X	X
Gaseous nitrogen valve actuation	--	--	--	--	X
	--	--	--	X	X

TABLE III. - SPACECRAFT PRESSURE-VESSEL QUALIFICATION - Continued

Tank function	Test performed				
	Vibration	Shock	Creep	Cyclic	Burst
CM reaction control system					
Pressurization	--	X	X	--	X
	X	X	X	X	X
	X	X	--	X	X
	X	X	--	--	X
Oxidizer	X	X	--	X	X
	X	X	--	--	--
Fuel	X	X	--	X	X
SM reaction control system					
Pressurization	X	--	X	--	--
	X	--	--	X	X
Oxidizer	--	--	--	X	X
	X	--	--	--	X
	X	--	--	--	--
	--	--	--	--	X
Fuel	X	--	--	X	X
	X	--	--	--	X
	--	--	X	--	X
	--	--	--	--	X
Secondary vessels Block II					
Oxidizer[a]	--	--	--	--	--
Fuel[b]	--	--	--	--	--

[a]Same as CM reaction control system oxidizer.

[b]Same as CM reaction control system fuel.

TABLE III. - SPACECRAFT PRESSURE-VESSEL QUALIFICATION - Continued

Tank function	Test performed				
	Vibration	Shock	Creep	Cyclic	Burst
CM fuel cell					
Cryogenic oxygen	--	--	--	--	X
	--	--	--	X	X
	--	--	--	--	X
	--	--	--	X	X
Cryogenic hydrogen	--	--	--	--	X
	--	--	--	X	X
	--	--	X	X	X
	--	--	X	X	X
Gaseous nitrogen pressurization	--	--	--	--	X
	--	--	--	--	X
	--	--	--	X	X
	--	--	--	X	X
	--	--	--	X	X
	--	--	--	X	X
Oxygen surge	X	X	--	X	X
	X	X	--	X	X
	X	X	--	X	X
	X	X	--	--	--
LM reaction control system					
Pressurization	X	--	X	X	X
	X	X	--	--	X
Oxidizer	X	X	--	X	X
	X	X	--	X	X
Fuel	X	X	--	X	X
	X	X	--	X	X
LM ascent propulsion system					
Pressurization	X	--	X	--	X
	X	X	X	X	X
Propellant	X	--	X	X	X

TABLE III. - SPACECRAFT PRESSURE-VESSEL QUALIFICATION - Concluded

Tank function	Test performed				
	Vibration	Shock	Creep	Cyclic	Burst
LM environmental control system					
Ascent stage gaseous oxygen	X X	X --	X X	X --	X X
Descent stage gaseous oxygen	X --	X --	X --	X --	X X
LM descent propulsion system					
Pressurization ambient	X X	X X	-- X	-- X	X --
Supercritical helium	X X	X X	-- --	X --	X --
Propellant	X	X	X	--	X

QUALITY ASSURANCE

The requirements for the quality-assurance programs of NASA contractors are delineated in NASA quality publication NPC 200-2. Applicable portions of this document were imposed by the NASA Manned Spacecraft Center (MSC) on pressure-vessel manufacturers at the beginning of hardware fabrication to ensure adequate control of processing and fabrication variables and to provide for the availability of pertinent information and data concerning materials properties, deviations from requirements, Material Review Board (MRB) actions, and test data on each pressure vessel.

Additional Requirements

Because of problems that had been experienced from the beginning of vessel fabrication to early 1967, a decision was made to evaluate each vessel on each Apollo spacecraft for flight worthiness before launch. Since that time, each Apollo pressure vessel has been accompanied at vehicle delivery by a data package or "pedigree" that contains a manufacturing and processing history, including any discrepancies, and a pressurization data log. This requirement is in addition to those contained in the NASA quality publication. In this way, each vessel has been fully characterized for individual

evaluation of structural integrity and projected life capability. The following specific information is contained in each data package.

1. Material and process specifications (submitted one time per generic vessel unless subsequently revised)

2. Weld parameters and repair history

3. Chemical analysis of materials (including weld wire)

4. Mechanical properties verification for materials

5. Certification of acceptance testing

6. Pressurization history (including fluids and times)

7. Fluid exposure history (other than during pressurization)

8. Discrepancy reports and reviews

9. Nondestructive evaluation requirements and certification

Inspection and Discrepancy Reports

Pressure vessels have been inspected by the contractor at prescribed stages during fabrication and jointly inspected by contractor/NASA representatives at mandatory inspection points incorporated throughout vessel fabrication and during subsequent system buildup. Discrepancy reports have been written for all anomalies or out-of-specification conditions detected during inspection or test. These discrepancy reports have been resolved by means of MRB action by responsible contractor and NASA representatives and are part of each data package. Particularly serious discrepancies such as anomalies requiring detailed stress analysis or generation of empirical data for materials evaluation have been resolved at higher levels but are reflected in MRB documentation.

Discrepancies originating at the prime contractor facilities can be classified generally as scratches, dents, or fit-up irregularities. Discrepancies originating at the subcontractor (vessel manufacturer) facilities can be classified generally as machining errors, scratches, dents, weld mismatch, weld porosity, dimensional anomalies, and, in one instance, a heat-treating error. The discrepancies have been random; no trends have been observed.

In the first 13 command and service modules and nine lunar modules, 176 and 123 vessel discrepancies, respectively, were found. The number of discrepancies, which is small considering the total number of vessels (926) involved, includes many that were minor, such as superficial scratches. The number of vessel discrepancies per spacecraft is shown in figures 10 and 11.

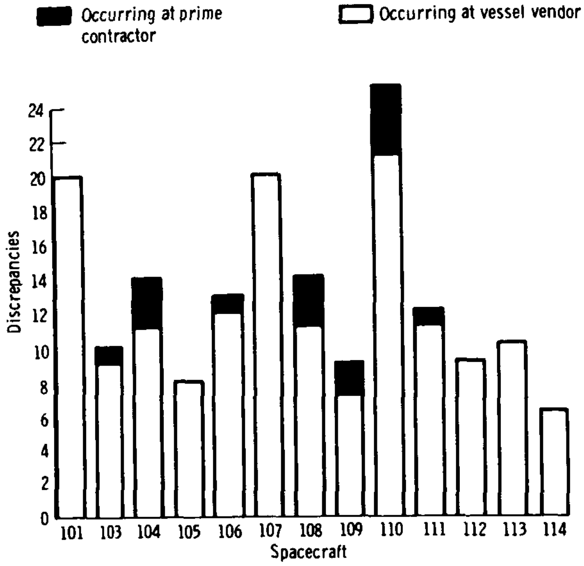


Figure 10. - Command and service module pressure-vessel discrepancies.

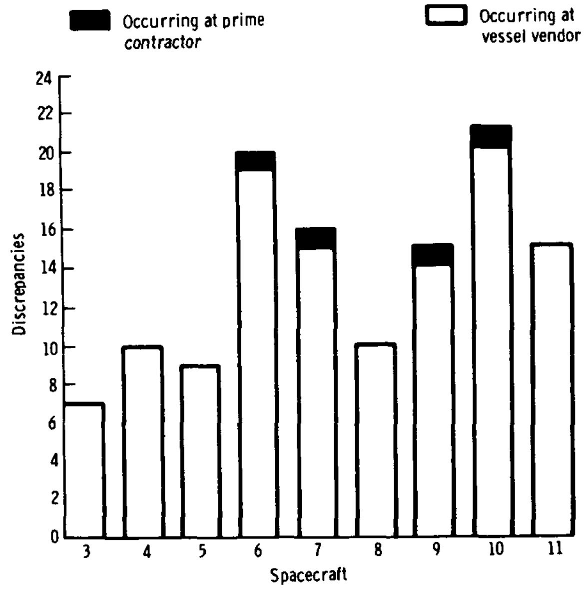


Figure 11. - Lunar module pressure-vessel discrepancies.

Nondestructive Testing

The major NDT methods that have been used on Apollo vessels are ultrasonic inspection of vessel details after the machining phases of fabrication, X-ray inspection, dye-penetrant inspection of welds, and dye-penetrant inspection of certain vessel membrane surfaces. In addition, magnetic-particle inspection has been used on steel vessels such as the lunar module descent stage gaseous oxygen vessel fabricated from D6AC steel. However, NDT has had some uncertainties that have introduced limitations in the use of these methods. For example, X-ray inspection can reveal surface and subsurface flaws, but flaw orientation can mask detection; whereas, penetrant inspection detects only flaws that are open to the surface. In addition, routine inspection methods are dependent on the technique and training of the inspector and the nature of the flaw. For this reason, a precise limit could not be assigned to the minimum size of the flaw or to the population that would be detected by the inspection methods.

In the case of some metallurgical flaws in the material, such as massive embrittled alpha in titanium or titanium-hydride formation at welds, no satisfactory method of NDT is known. Such flaws are rare but have caused failure in pressure vessels. A neutron radiography technique has met with some success but requires development.

Because of the uncertainties involved, NDT techniques have not been used alone to guarantee the integrity of pressure vessels. However, NDT techniques have been excellent means of monitoring fabrication control and ensuring production consistency and compliance with specification requirements. In this respect, the application of NDT has facilitated the delivery of basically sound pressure vessels that have been controlled during use according to fracture-mechanics criteria to ensure safe operation.

APPLICATION OF FRACTURE-MECHANICS TECHNOLOGY

The heat treatment of many pressure-vessel alloys to high strength levels and use at high stresses (low safety factors) results in a potentially increased sensitivity to small flaws and various environments. Limitations in present nondestructive inspection techniques could allow some relatively small flaws in the vessels to escape detection. Therefore, attention had to be given to the method by which these flaws could propagate during ground testing and flight to ensure that such flaws would not result in failure of the pressure vessels. In 1967, approximately 3 years after vessel fabrication was begun, the vessel proof test became a valuable inspection technique using a fracture-mechanics approach and provided a baseline for postfabrication vessel analysis.

The concepts of linear-elastic fracture mechanics (refs. 1 and 2) have been used to examine the relationship between the maximum flaw size in a pressure vessel that passes a proof test and the subsequent subcritical crack growth possible in ground-test and flight environments.

The fracture-toughness/stress-intensity approach to fracture analysis generally has been accepted as the best available means of using fracture-mechanics technology in practical problems. The fracture-toughness parameter describes the maximum flaw size that a material can tolerate without rapid fracture when stressed to a prescribed level and is the value obtained for the stress-intensity factor that results in flaw instability (structural failure). This value then is called the critical stress intensity or fracture toughness. Any stress intensity at a flaw that is less than the fracture-toughness value is subcritical.

Fracture-toughness (apparent K_{IC}) properties have been obtained for Apollo pressure-vessel materials. To investigate the compatibility of a pressure-vessel material with the fluid the vessel is intended to contain, stressed vessel-material specimens having cracks introduced of known size and shape have been exposed to the environment in question. The determination was made that, for each environment tested, an apparent threshold stress intensity K_{th} exists below which cracks in a given vessel alloy do not grow. The experimental threshold values for various Apollo vessel materials and environments are listed in table IV. Most of the threshold data in table IV have been developed for time exposures consistent with Apollo requirements. For missions longer than those of the Apollo Program, long time data must be obtained. A method for determining thresholds is described in reference 3.

TABLE IV. - THRESHOLD VALUES FOR APOLLO PRESSURE-VESSEL MATERIALS AND SELECTED ENVIRONMENTS

Alloy	Temperature, °F	Threshold stress intensity K_{th}, percent K_{IC}							
		Nitrogen tetroxide	Monomethyl hydrazine	Aerozine-50	Trichlorotrifluoroethane		Air, helium, nitrogen, and oxygen	Distilled water	Liquid oxygen
					Forging	Weld			
Titanium 6Al-4V	66	82	88	83	61	47	90	86	--
	70	81	82	82	60	46	90	85	--
	74	80	81	81	60	45	90	84	--
	78	79	81	81	59	44	90	83	--
	82	78	80	80	58	43	90	82	--
	86	77	80	80	58	42	90	80	--
	90	76	79	79	57	41	90	79	--
	94	74	78	78	56	40	90	78	--
	98	73	77	77	55	39	90	76	--
	102	71	76	76	54	38	90	74	--
	106	70	75	75	53	37	90	72	--
	110	68	74	74	--	--	--	--	--
	114	67	73	73	--	--	--	--	--
	118	65	71	71	--	--	--	--	--
	122	63	70	70	--	--	--	--	--
	126	52	68	68	--	--	--	--	--
	130	60	67	67	--	--	--	--	--
	134	58	65	65	--	--	--	--	--
	138	56	64	64	--	--	--	--	--
	142	55	62	62	--	--	--	--	--
	146	53	60	60	--	--	--	--	--
	150	51	59	59	--	--	--	--	--
AM 350	85	--	--	--	--	--	90	--	--
Inconel 718	85	--	--	--	--	--	90	80	--
	-297	--	--	--	--	--	--	--	85
Titanium 5Al-2.5Sn	85	--	--	--	--	--	90	80	--

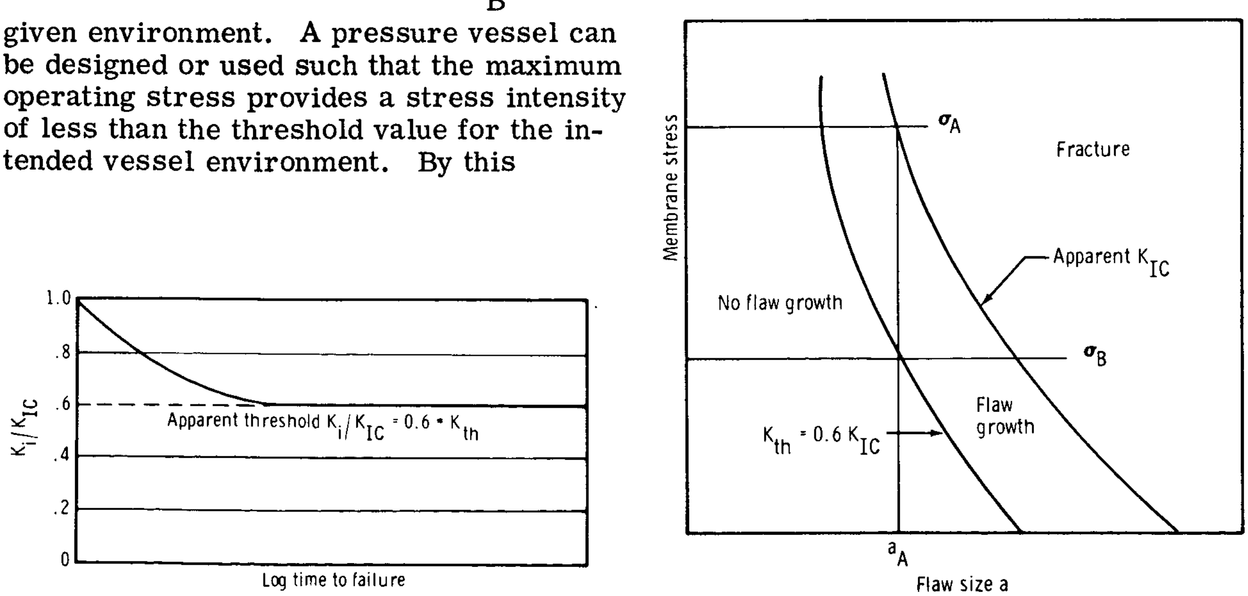
TABLE V. - APOLLO PRESSURE-VESSEL STRUCTURAL FAILURES

Pressure vessel	Failures	Cause	Date
SM/RCS propellant	10	Nitrogen-tetroxide stress corrosion	1965 to 1966
SM/SPS propellant	[a]2	Methanol stress corrosion	October 1966
SM/SPS propellant	1	Weld cracks (proof)	October 1963
SM/electrical power system gaseous nitrogen	1	Crack from embrittled weld repair (leak test)	April 1967
LES motor case	2	Weld cracks plus incompatible fluid (water) (proof)	August 1967
LM descent stage gaseous oxygen	1	Material defect plus incompatible fluid (water) (acceptance test)	June 1966
LM descent stage propellant	1	Massive alpha defect (proof)	March 1965
SM/electrical power system cryogenic oxygen	[a]1	Internal ignition resulting in overpressurization failure	April 1970

[a]Vessels were installed in spacecraft.

The application of the data from the fracture toughness (apparent K_{IC} or critical stress intensity) and the subcritical flaw-growth threshold K_{th} to a pressure vessel may be summarized as follows. The ratio of the initial stress intensity K_i (stress intensity at the flaw tip at the beginning of test) to the critical stress intensity K_{IC} as a function of the time to failure for cracked specimens is obtained experimentally and gives a curve as shown in figure 12(a). The stress intensity corresponding to the horizontal portion of the curve is the apparent threshold value K_{th} for onset of flaw growth in the test environment. An increase of the stress intensity above this value can result in environmental flaw growth. The flaw then can continue to grow to the critical size at which rapid crack growth (failure) occurs. Below the threshold value, environmental flaw growth does not occur.

The relationships of a proof stress σ_A, the flaw screened a_A, and the maximum permissible operating stress σ_B for a pressure vessel based on fracture-mechanics data are illustrated in figure 12(b). If a proof test conducted at a stress σ_A does not cause failure, the assumption can be made that no equivalent flaw equal to or greater than a_A exists in the vessel at the end of the proof test. By use of this information, the conclusion can be made that crack growth will not occur during the constant-stress operational life if the pressure vessel is used at a stress level less than σ_B in the given environment. A pressure vessel can be designed or used such that the maximum operating stress provides a stress intensity of less than the threshold value for the intended vessel environment. By this



(a) Log time to failure as a function of K_i/K_{IC}.

(b) Flaw size as a function of membrane stress.

Figure 12. - Application of static fracture toughness and subcritical flaw growth to pressure-vessel analysis.

method of analyzing pressure vessels using the modified Irwin equation from reference 2, safe operation could be predicted from the ratio of the proof pressure to the operating pressure and from the threshold or stress-intensity ratio required for crack growth.

Although during flight the pressure in Apollo vessels is noncyclic, the effect of cyclic flaw growth during leak checks and other pressure tests of Apollo vessels also had to be considered in vessel analysis. The maximum size flaw screened by the proof test was assumed to exist, and subcritical fatigue flaw growth caused by cyclic stress was evaluated and incorporated into each analysis. For example, the cyclic flaw-growth rate for 6Al-4V titanium alloy was determined experimentally in terms of stress intensity as a function of the number of cycles to failure as described in reference 4. From these data, a curve showing flaw growth rate per cycle at various K_i/K_{IC} levels can be constructed and used in vessel analysis.

To analyze a pressure vessel, three types of basic data are needed.

1. The fracture toughness K_{IC} of the material

2. The constant-stress flaw-growth threshold K_{th} in the environments to which the vessel will be exposed

3. The rate of cyclic growth

Fracture-mechanics analyses of Apollo pressure vessels and determinations of environmental compatibility thresholds were initiated at the MSC in late 1966. The effort resulted in the initiation of pressurization restrictions and environmental exposure control of all vessels by mid-1967. The fracture-mechanics criteria and the techniques for analyzing and controlling Apollo pressure vessels were contractually imposed on the Apollo spacecraft contractors. The implementation of these specifications established common and consistent postfabrication evaluation procedures for all Apollo spacecraft pressure vessels. Basic overall considerations and guidelines for fracture control of pressure vessels are presented in reference 5.

PROBLEMS ASSOCIATED WITH VESSELS USED IN APOLLO SPACECRAFT

The pressure-vessel problems experienced by the MSC and associated Apollo contractors are summarized in this section. Hardware problems that resulted in structural failures are listed in table V. Only three failures occurred on vessels installed in spacecraft: two during systems tests and one during the flight of Apollo 13. Generally, structural failures resulted from unexpected environmental-stress-cracking effects on the vessel materials or insufficient control of materials or processes. Specific problems and resolutions are discussed in the following paragraphs. Potential problems that were not actually experienced but that required evaluation and resolution are discussed in the last three paragraphs in this section.

Specific Problems

Nitrogen tetroxide incompatibility with 6Al-4V titanium-alloy pressure vessels. - In 1965, a 6Al-4V titanium-alloy vessel containing nitrogen tetroxide (N_2O_4) under pressure suffered localized stress-corrosion failure. Because of known reactions between titanium and other oxidizers, extensive test programs to establish compatibility between N_2O_4 and the vessel alloy had been conducted successfully before 1965. Investigation of the cause of the failure resulted in the unexpected discovery that the alloy would undergo general stress corrosion in certain grades of N_2O_4 (refs. 6 and 7). This discovery was particularly serious for the Apollo Program because 17 titanium vessels on each spacecraft contain N_2O_4.

The chemical makeup of the N_2O_4, primarily the nitric oxide (NO) content, determined whether stress corrosion would occur. Previous tests had been conducted using N_2O_4 that had a relatively high NO content. Subsequent investigations showed that stress corrosion would not occur with NO contents greater than 0.5 percent. The actual lower limit has not been defined. At the MSC, a specification was generated for N_2O_4 requiring an NO content of 0.8 ± 0.2 percent to prevent recurrence of the problem. In addition, each lot of N_2O_4 used for Apollo flights has been tested using precracked 6Al-4V titanium-alloy specimens. These data have been analyzed using fracture-mechanics principles to verify that the stress-corrosion threshold was sufficiently high to preclude environmental crack growth in flight. The application of fracture mechanics to Apollo vessels is discussed in a separate section.

As a precautionary measure, each lot of fuel (Aerozine-50 and monomethyl hydrazine) used for Apollo flights has been tested using precracked specimens to verify that the stress-corrosion thresholds are acceptable because all possible combinations and levels of impurities permitted by specification may not have existed in earlier successful compatibility tests.

Methanol incompatibility with 6Al-4V titanium-alloy pressure vessels. - Substitute fluids that simulate the specific gravity and flow characteristics of the propellants have been used to avoid the hazards associated with hypergolics when testing propulsion systems installed in spacecraft. Methanol was used to simulate Aerozine-50 during flow tests of the SM propulsion system at operating pressures.

The first of two failures with methanol occurred on October 1, 1966, when a Block II SM vessel developed three separate leaks near the bottom girth weld while at normal operating pressure. Originally, the cause of the failure appeared to be localized stress corrosion caused by an undetected materials anomaly. Twenty-four days later, a Block I vessel containing methanol failed while pressurized to maximum operating pressure. The failure was explosive, rupturing an adjacent vessel and destroying the SM. Because the vessel was not filled to capacity, the ullage contributed to the high level of damage.

Investigation of the failures showed that pure anhydrous methanol is incompatible with the 6Al-4V titanium-alloy vessel material and results in severe stress-corrosion

attack (ref. 8). An SPS vessel that had successfully undergone tests with methanol was subjected to a proof pressure test and failed at 90 percent of the design proof level, showing that damage to the vessel had occurred during methanol exposure although failure had not occurred. Therefore, methanol was eliminated from use in Apollo pressure vessels.

Subsequently, with initiation of fracture-mechanics evaluation techniques, all other fluids used in Apollo vessels were tested using precracked specimens. As a result, trichloromonofluoromethane was restricted from use because of a relatively low stress-corrosion threshold although hardware failure had not occurred.

Failure of a service propulsion system main propellant vessel during proof test. - In 1963, during an acceptance proof test, a failure of a Block I vessel occurred that was attributable to the development of an axial fracture in the heat-affected zone of a dome-to-cylinder weld. The fracture had transgranular cleavage of a type observed in conjunction with contamination of the 6Al-4V titanium alloy. The source of the contamination was not definitely established. However, the contamination probably occurred during welding or preparation for welding. The procedures and techniques were reviewed and modified in the areas that would protect against contamination during the welding operation. Handling with clean-gloved hands was made a requirement, and a vapor-blast cleaning procedure was initiated shortly before welding to ensure clean surfaces. No subsequent occurrences of contamination were detected in SPS propellant-vessel welds.

Acceptance test failure of a lunar module descent gaseous oxygen vessel. - An LM descent stage gaseous oxygen pressure vessel made of D6AC steel failed during acceptance testing. Failure analysis showed that the origin of the failure was a preexisting crack in the radius of the mounting boss. During acceptance testing, which consisted of pressure cycling the vessel in a water bath, the crack grew. The D6AC steel has a very low flaw-growth threshold in water. The tank manufacturer had been directed by the LM contractor not to use water as a pressurizing medium. Unfortunately, no mention was made of the medium in which the vessel was immersed during testing, and the use of water in this application was not discovered before the failure. Another contributing discrepancy was omission of inspection. The final machined boss areas received no detailed nondestructive testing or inspection after machining. The size of the preexisting crack in the failed vessel was of such magnitude that the vessel would have been rejected.

Subsequently, water was replaced by a more compatible fluid, trichlorotrifluoroethane. All boss areas have been dye checked and magnaflux inspected for flaws; radiographic inspection was instituted on all domes before welding. Subsequent rigorous environmental tests of sample vessels have completely qualified the design and use of the vessels on Apollo spacecraft.

Failure of launch escape system motor cases during proof tests. - In 1967, two LES motor cases made of 4335V steel failed during proof testing. These cases, and others in the same lot, had been welded with a filler wire having a higher carbon content than had been used on previous lots, including the qualification cases. This unauthorized substitution made the cases more susceptible to cracking in the weld areas and more susceptible to attack by water (the pressurizing fluid) while under stress. As a result, all cases in the affected lot were restricted from flight use. In subsequent lots,

oil was substituted for water as a pressurizing fluid. Quality-assurance requirements were revised to ensure that all fabrication steps and tests were accomplished in a satisfactory manner. Additional cases have been fabricated and tested under the new requirements with no recurrence of the problem.

Massive alpha inclusions in 6Al-4V titanium alloy. - An LM descent propulsion system (DPS) vessel failed during a hydrostatic acceptance proof test at 267 psig, which was 74 percent of the required 360-psig proof pressure. A metallurgical investigation showed that the failure was caused by a localized microstructure abnormality consisting of "massive" alpha-phase structure in the upper dome. A second instance of massive alpha inclusion was detected in an LM ascent propulsion system (APS) vessel dome during a hand-blending phase of fabrication because of the comparative hardness. The dome was rejected and therefore never subjected to a proof test.

Alpha inclusions of this sort are rare but, if they are present, cannot be detected by the standard NDT techniques used. Reliance on the proof test to screen a gross condition in a finished pressure vessel has been the only practicable approach. Because the condition cannot be detected at the time of acceptance of the vessel forgings, a considerable dollar loss is experienced with failure of a completed vessel. Although the occurrence of massive alpha is rare, the development of a suitable NDT technique may save costs and add confidence in the future use of titanium pressure vessels.

Failure of an electrical power system gaseous nitrogen pressure vessel. - In 1967, an electrical power system (EPS) nitrogen vessel leaked in the girth weld during a pressure decay test. Investigation of the failure disclosed that a repaired area of the weld was contaminated with oxygen, resulting in an embrittled condition that was susceptible to crack initiation and growth under cyclic conditions. An evaluation of the weld repair technique and equipment showed that a high probability of oxygen contamination existed during weld repair. Investigation of other nitrogen tanks that had weld repairs verified that oxygen contamination was a problem. As a result, all EPS nitrogen vessels that had weld repairs were deleted from the Apollo Program and the repair technique was modified. Contamination was not present in unrepaired vessels, and no subsequent problems have arisen when repairs have been required.

Failure of a cryogenic oxygen vessel during the flight of Apollo 13. - In February 1970, the Apollo 13 spacecraft experienced a rapid loss of pressure in the number 2 liquid oxygen vessel, which is fabricated from Inconel 718 alloy. Essentially, the findings of the investigation of the Apollo 13 anomaly indicated that ignition occurred inside the vessel at a point of degraded Teflon wire insulation. A fire propagated rapidly inside the vessel, increasing the temperature and pressure until the strength capability of the vessel itself was exceeded and failure occurred.

The structural capability of the oxygen vessel had been demonstrated in qualification tests and on previous Apollo flights. Inconel 718 was also known to be compatible with liquid oxygen. The fault existed in internal design where electrical components, Teflon-coated wire, and terminals exposed directly to an oxidizing environment resulted in a hazard under certain adverse conditions.

Potential Problems

Potential hydride formation in titanium-alloy-vessel welds made with unalloyed filler wire. - An explosion of a Saturn S-IVB stage during a test in March 1967 was attributed to the failure of a 6Al-4V titanium-alloy pressure vessel containing helium gas. The vessel had inadvertently been welded using unalloyed filler wire instead of the specified 6Al-4V titanium-alloy filler wire. The failed weld had severe titanium-hydride banding that weakened the weld and ultimately resulted in vessel failure at operating stress. Investigators of the failure postulated that the hydrides formed over a period of time in the region of the relatively abrupt change in hydrogen solubility between the 6Al-4V titanium alloy and the essentially unalloyed titanium weld. It was suggested that hydrogen migrated under stress conditions from a region of high solubility (alloy vessel material) to a region of low solubility (unalloyed weld) and precipitated as titanium hydrides upon reaching this zone.

The latent occurrence of hydrides in the failed S-IVB vessels caused concern about the integrity of the SPS, DPS, and APS 6Al-4V titanium-alloy propellant vessels that are welded, by requirement, with unalloyed filler wire. A comprehensive program was undertaken to evaluate the Apollo welds, and it was determined that the concern about latent hydride formation in the Apollo welds was unwarranted.

In summary, the S-IVB helium-vessel weld was different geometrically and thicker (0.452 inch) than the Apollo welds (0.070 and 0.090 inch), which use unalloyed wire. In the Apollo welds (including repaired welds that have additional unalloyed filler wire), apparently sufficient alloying exists in the weld nugget to preclude a hydride problem.

Conversely, some Apollo titanium vessels are required by specification to be welded with alloy filler wire. These vessels are relatively thick and more closely approximate the geometry and conditions of the S-IVB weld. To ensure that these welds were made using alloy wire, an eddy-current technique was used that would distinguish between welds made with alloyed or unalloyed wire. No instances of wrong filler-wire use were detected.

Potential alpha-stringer structure problem in 6Al-4V titanium alloy. - The 6Al-4V titanium alloy has been used for 47 vessels in the various Apollo spacecraft propulsion systems. Therefore, a potential problem with this material was reason for concern because a serious general material anomaly would have a severe negative impact on the Apollo Program.

Briefly, the metallographic structure of the alloy normally consists of a beta-phase matrix that has a dispersion of equiaxed alpha-phase "islands." During tests to verify the properties of a certain lot of forgings for LM vessels, comparatively low elongation values were noted on a number of tensile test specimens taken from forging trim rings. All other mechanical properties were within specification limits. Metallographic examination showed that many of the alpha constituents in the structure had an elongated shape and were representative of alpha platelets or "stringers" rather than of the equiaxed alpha islands. A definite correlation was established between the low elongation and the presence of stringers.

A program was conducted to evaluate normal and alpha-stringer structure under identical test conditions. Results of the tests indicated that no significant differences

in behavior existed between the two structures except for ductility. The presence of alpha-stringer structure would not significantly affect the performance capability of the 6Al-4V titanium-alloy pressure vessels as long as elongation values were greater than the minimum specification limit of 8 percent.

Acicular or elongated structure must not be confused with the "massive" or "low density" alpha-inclusion problem that is a threat to structural integrity.

Potential failure of lunar module descent propulsion system vessels during flight. - Cyclic-flaw-growth analysis for the LM DPS vessels showed that the maximum flaw that could exist in the vessels after a normal proof test could grow during ground pressurizations to a size that would give a stress intensity above propellant threshold values during flight. To provide added cyclic life, a cryogenic liquid-nitrogen proof test was instituted and added to the existing ambient proof-test requirements. The cryogenic proof test has benefited by two changes in material properties that occur in the 6Al-4V titanium alloy with temperature. At -320° F, the alloy strength is increased, providing for a higher proof-test pressure (430 psi), and the fracture toughness of the alloy is slightly decreased, making the alloy sensitive to smaller flaws during the proof test. Therefore, the cryogenic proof test screened to a flaw size much smaller than the ambient proof test, providing increased flaw-growth capability during vessel use. This capability eased test restrictions and made contingency pressure cycles available for retests of the DPS if required.

PRESSURE-VESSEL MANAGEMENT

During the early phases of the Apollo Program (to the end of 1966), each NASA subsystem manager had sole responsibility for the pressure vessels in his respective subsystem. Because the background and training of the subsystem managers varied, inconsistencies evolved in pressure-vessel requirements and usage.

As the Apollo Program progressed, many problems with pressure vessels required specialized skills and training not possessed by the subsystem managers. These included problems relating to metallurgical considerations (welding, heat treating, forging, and so forth) and service problems involving materials compatibility and safe operation analysis.

In 1967, a decision was made at the MSC that spacecraft pressure vessels would be treated as a unique subsystem with designated responsibility and that requirements and use criteria would be standardized. Definitions of pressure-vessel terms also were standardized for the Apollo Program, as presented in the appendix. An MSC technical monitor, who had the following general responsibilities, was appointed.

1. Ensuring the structural integrity of pressure vessels

2. Implementing fracture mechanics to ensure that all flight vessels will meet mission requirements (pressures, temperatures, and number of cycles of pressurization)

3. Ensuring that all fluids to which vessels are exposed after acceptance tests are compatible with tank material

4. Ensuring that required structural safety factors are maintained

5. Examining qualifications tests for adequacy

6. Assessing fabrication procedures and methods

7. Reviewing manufacturing discrepancies and resolutions

8. Participating in the resolution of discrepancies where required

9. Establishing allowable pressure/temperature relationships for vessels during each Apollo flight

Single points of contact and responsibility for pressure vessels also were designated at the prime contractor facilities to interface with the MSC monitor, thus facilitating workable pressure-vessel coordination and control. In addition, an MSC quality monitor was assigned to interface with the MSC technical monitor and the designated prime contractor point of contact. It was the responsibility of the quality monitor to ensure contractor compliance with the quality-assurance data-package requirements.

CONCLUDING REMARKS

During the Apollo Program, pressure vessels have been critical to spacecraft operation and safety. In addition to stringent material and fabrication controls, an increase in the level of confidence associated with pressure-vessel use was achieved by means of the application of fracture-mechanics criteria to provide confidence in establishing fluid/pressure/temperature limitations for pressure-vessel operations.

Pressure-vessel safety factors as low as 1.5 have been shown to be practical, provided proper materials, processes, and usage evaluations are made. Stringent material and fabrication control must be implemented to ensure consistency in metallurgical factors that, if varied, can significantly affect vessel performance. Material properties may be highly sensitive to variations in composition, manufacturing methods, or service exposure. Unfortunately, metallurgical analysis of vessel failures usually provided the first evidence of material factors adversely affecting performance. The reasons for the problems and steps to preclude them were generally "after the fact." An analysis of the application supplemented by required testing of material before design, therefore, is of major importance. Compatibility of pressurants with the vessel material under use conditions must be established, and subsequent fluid and pressure control consistent with test data is mandatory. Manufacturing methods and service environments must be evaluated thoroughly. The proper analysis and use of materials for pressure-vessel service can be achieved only by means of full coordination among systems engineers, designers, stress analysts, and materials specialists in meeting systems requirements. Responsibility must be delegated to ensure that all are involved.

RECOMMENDATIONS

Based on Apollo spacecraft experience, the following recommendations are made to reduce risk and to ensure pressure-vessel integrity on future programs.

1. Apply fracture-mechanics criteria in pressure-vessel design.

2. Evaluate design and materials selection of components to be used inside pressure vessels for potential adverse conditions and effects.

3. By use of the fracture-mechanics threshold approach, establish the compatibility of the vessel materials with each fluid which will contact the material while stressed.

4. Actively protect against the use of improper or unauthorized materials during vessel fabrication.

5. Verify that weld repair techniques are sufficient to provide repaired areas that have integrity equal to unrepaired welds.

6. Establish consistent control requirements and criteria for regulation of pressurizations.

7. Establish definite responsibility and authority in pressure-vessel activity.

8. Exercise discretion when considering the elimination, because of cost savings, of any quality-control documentation requirements or testing of pressure vessels.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, March 3, 1972
914-13-20-06-72

REFERENCES

1. Irwin, G. R.: Analysis of Stresses and Strains Near the End of a Crack. J. Appl. Mech., vol. 24, 1957, p. 361.

2. Tiffany, C. F.; Masters, J. N.; and Pall, F.: Some Fracture Considerations in the Design and Analysis of Spacecraft Pressure Vessels. Presented at ASM National Metals Congress (Chicago), Oct. 1966.

3. Tiffany, C. F.; and Masters, J. N.: Investigation of the Flaw Growth Characteristics of 6Al-4V Titanium Used in Apollo Spacecraft Pressure Vessels. NASA CR-65586, 1967.

4. Masters, J. N.: Cyclic and Sustained Load Flaw Growth Characteristics of 6Al-4V Titanium. NASA CR-92231, 1968.

5. Tiffany, C. F.: Fracture Control of Metallic Pressure Vessels. NASA SP-8040, 1970.

6. Johnson, R. E.; Kappelt, G. F.; and Korb, L. J.: A Case History of Titanium Stress Corrosion in Nitrogen Tetroxide. Am. Soc. for Metals, 1966.

7. Kappelt, G. F.; and King, E. J.: Observations on the Stress Corrosion of the 6Al-4V Titanium Alloy in Nitrogen Tetroxide. Presented at AFMC 50th Anniversary Corrosion of Military and Aerospace Equipment Technical Conference (Denver), May 1967.

8. Johnston, R. L. et al.: Stress Corrosion Cracking of Ti-6Al-4V Alloy in Methanol. NASA TN D-3868, 1967.

APPENDIX

PRESSURE-VESSEL DEFINITIONS

Pressure vessel: Vessel containing a compressed fluid with an energy equal to or exceeding 14 250 ft-lb (0.01 pound trinitrotoluene equivalent) based on the adiabatic expansion of a perfect gas

Normal operating pressure: Regulated pressure during system operation or the nominal fill value for pressurization tanks

Regulator lockup pressure: Back pressure at which the regulator completely stops the flow of pressurizing gas

Maximum design operating pressure: Pressure as limited by relief provisions or maximum expected environment

Proof pressure: Pressure that each vessel must have sustained to be acceptable for use in the spacecraft

Design burst pressure: Maximum pressure that a vessel is designed to sustain without rupture

Safety factor: The ratio of design burst pressure to maximum design operating pressure

Subsystem pressure verification test: A single pressure test of the subsystem at a specified pressure above maximum design operating pressure to verify subsystem integrity

Subsystem component installation pressure verification test: A pressure test conducted at maximum design operating pressure or below to verify joints after replacement of components

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